

Search for the U-boson in the process
 $e^+e^- \rightarrow \mu^+\mu^-\gamma, U \rightarrow \mu^+\mu^-$ with the KLOE detector

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We present a search for a new light vector boson, carrier of a “dark force” between WIMPs, with the KLOE detector at DAΦNE. We analysed $e^+e^- \rightarrow \mu^+\mu^-\gamma$ ISR events corresponding to an integrated luminosity of 239 pb^{-1} to find evidence for the $e^+e^- \rightarrow U\gamma, U \rightarrow \mu^+\mu^-$ process. We found no U vector boson signal and set a 90% CL upper limit on the ratio of the U boson and photon coupling constants between 1.6×10^{-5} to 8.6×10^{-7} in the mass region $520 < M_U < 980 \text{ MeV}$. A projection of the KLOE sensitivity for the $\mu\mu\gamma$ and $\pi\pi\gamma$ channels at full statistics and extended muon acceptance is also presented.

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1. Introduction

Many extensions of the Standard Model (SM) [1–5] assume that dark matter (DM) is made up of new particles charged under some new interaction mediated by a new gauge vector boson called U (also referred to as

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dark photon or A'). The U boson can kinetically mix with the ordinary photon through high-order diagrams, providing therefore a small coupling with SM particles [1–5]. The coupling strength can be expressed by a single factor, ε , equal to the ratio of dark and Standard Model electromagnetic couplings [1]. A U boson with mass of $\mathcal{O}(1\text{GeV})$ and ε in the range 10^{-2} – 10^{-7} could explain all puzzling effects observed in recent astrophysics experiments [6–12]. By using a data sample corresponding to an integrated luminosity of 239 pb^{-1} , KLOE investigated the the radiative $U\gamma$ production with $U \rightarrow \mu^+\mu^-$. New searches are foreseen to exploit the full KLOE statistics for the $\mu^+\mu^-\gamma$ channel and also to search for the $U \rightarrow \pi^+\pi^-$ decay.

2. The KLOE detector

The KLOE detector operates at DAΦNE, the Frascati ϕ -factory. It consists of a large cylindrical drift chamber (DC) [13], surrounded by a lead scintillating-fiber electromagnetic calorimeter (EMC) [14]. A superconducting coil around the EMC provides a 0.52 T magnetic field along the beam axis. EMC energy and time resolutions are $\sigma_E/E = 0.057/\sqrt{E(\text{GeV})}$ and $\sigma_t = 57\text{ ps}/\sqrt{E(\text{GeV})} \oplus 100\text{ ps}$, respectively. The drift chamber has only stereo sense wires, it is 4 m in diameter, 3.3 m long and operates with a low- Z gas mixture (helium with 10% isobutane). Spatial resolutions are $\sigma_{xy} \sim 150\text{ }\mu\text{m}$ and $\sigma_z \sim 2\text{ mm}$. The momentum resolution for large angle tracks is $\sigma(p_\perp)/p_\perp \sim 0.4\%$.

3. $\mu^+\mu^-\gamma$ data analysis

The $\mu^+\mu^-\gamma$ event selection requires two tracks of opposite charge with $50^\circ < \theta < 130^\circ$ and an undetected photon whose momentum, computed according to the $\mu\mu\gamma$ kinematics, points at small polar angle ($\theta < 15^\circ, > 165^\circ$) [15, 16]. These requirements limit the range of $M_{\mu\mu}$ to be larger than 500 MeV and greatly reduce the contamination from the resonant and Final State Radiation (FSR) processes: $e^+e^- \rightarrow \phi \rightarrow \pi^+\pi^-\pi^0$, $e^+e^- \rightarrow \pi^+\pi^-\gamma_{\text{FSR}}$ and $e^+e^- \rightarrow \mu^+\mu^-\gamma_{\text{FSR}}$. The above selection criteria are also satisfied by $e^+e^- \rightarrow e^+e^-\gamma$ radiative Bhabha events. To obtain additional separation between electrons and pions or muons, a particle identification estimator (L_i), based on a pseudo-likelihood function using time-of-flight and calorimeter information is used [15, 16]. Events with both tracks satisfying $L_i < 0$ are rejected as $e^+e^-\gamma$ with a $\pi\pi\gamma/\mu\mu\gamma$ loss less than 0.05%. Pions and muons are identified by means of the variable M_{trk} defined as the mass of oppositely-charged particles in the $e^+e^- \rightarrow x^+x^-\gamma$ process in which we assume the presence of an unobserved photon and that the tracks belong to particles of the same mass with momentum equal to the observed value.

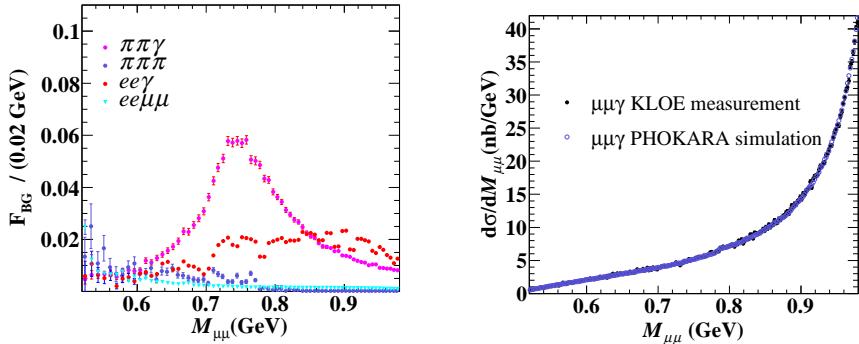


Fig. 1. Left: Fractional backgrounds to the $\mu\mu\gamma$ signal; see insert for symbols. Right: Comparison of data (full circles) and simulation (open circles) for $\mu^+\mu^-\gamma$ cross section.

The M_{trk} values between 80–115 identify muons while M_{trk} values > 130 MeV identify pions. A cut on the quality of the fitted tracks, parametrized by the error on M_{trk} , $\sigma_{M_{\text{trk}}}$, has been implemented to further improve the π/μ separation [15]. At the end of the analysis chain, residual backgrounds consisting of $e^+e^- \rightarrow e^+e^-\gamma$, $e^+e^- \rightarrow \pi^+\pi^-\gamma$ and $e^+e^- \rightarrow \phi \rightarrow \pi^+\pi^-\pi^0$ are still present. The last two contributions have been evaluated from Monte Carlo (MC) simulation while the $e^+e^- \rightarrow e^+e^-\gamma$ events have been estimated directly from data [15, 16]. Additional background from $e^+e^- \rightarrow e^+e^-\mu^+\mu^-$ is at the percent level below 0.54 GeV and decreases with $M_{\mu\mu}$. Fig. 1 left shows the fractions of the background processes, F_{BG} , as a function of $M_{\mu\mu}$ while Fig. 1 right shows the measured $\mu\mu\gamma$ cross section compared with the NLO QED calculations, using the MC code PHOKHARA [17]. The agreement between measurement and the PHOKHARA simulation is excellent, proving analysis consistency. No structures are visible in the $M_{\mu\mu}$ spectrum.

4. Limit on U -boson coupling and future prospects

To exclude small U -boson signals we extracted the limit on the number of U -boson candidates at 90% of confidence level (CL) through the CLS technique [18]. We compared the expected and observed $\mu^+\mu^-\gamma$ yield, and a MC generation of the U -boson signal which takes into account the resolution in $M_{\mu\mu}$ (from 1.5 MeV to 1.8 MeV as $M_{\mu\mu}$ increases). The limit on the kinetic mixing parameter has been extracted by means of:

$$\varepsilon^2 = \frac{N_{\text{CLS}} / (\epsilon_{\text{eff}} \times L)}{H \times I}, \quad (1)$$

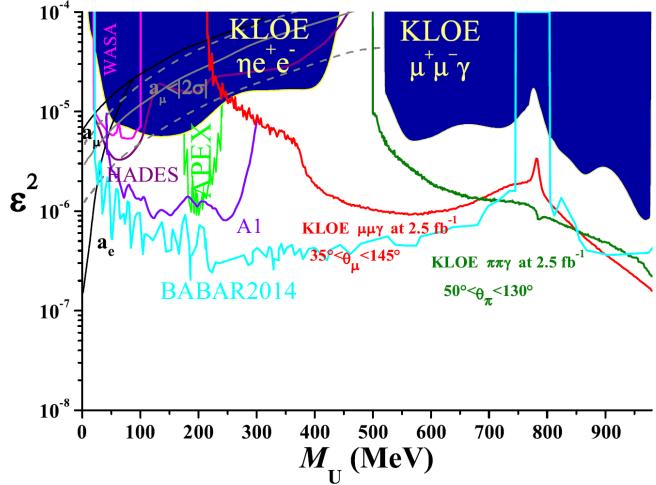


Fig. 2. 90% CL exclusion plot for ε^2 as a function of the U -boson mass (blue) [15]. Limits from A1 [19] (violet), Apex [20] (green), KLOE $\phi \rightarrow \eta e^+ e^-$ [21, 22] (blue), WASA [23] (magenta), HADES [24] (purple) and BaBar (cyan) [25] are shown. The black and grey lines are the limits from the muon and electron anomaly [26], respectively. KLOE sensitivity for $\mu\mu\gamma$ and $\pi\pi\gamma$ at 2.5 fb^{-1} and $35^\circ (50^\circ) < \theta_{\mu(\pi)} < 145^\circ (130^\circ)$ are also shown (red and green lines, respectively).

where ϵ_{eff} represents the overall efficiency (1-15% as $M_{\mu\mu}$ increases [15]), L is the integrated luminosity, H is the radiator function obtained from QED including NLO corrections, and I is the effective U cross section [3]. The resulting exclusion plot on the kinetic mixing parameter ε^2 , in the 520–980 MeV mass range, is shown in Fig. 2. In the same plot, other limits in the mass range below 1 GeV are also shown [19–26]. Our 90% CL limit is between 1.6×10^{-5} and 8.6×10^{-7} in the 520–980 MeV mass range [15].

An upgrade of the presented analysis is foreseen by employing the full KLOE data statistics corresponding to an integrated luminosity of 2.5 fb^{-1} and by extending the muon polar angle acceptance from 50° to 35° and from 130° to 145° . The KLOE reach in sensitivity by considering a 2 MeV invariant mass resolution is presented in Fig. 2 (red line) at $N_U/\sqrt{N_{\text{QED}}} = 2$. The sensitivity loss due to the ρ meson around 770 MeV is due to the branching fraction of the $U \rightarrow \mu^+ \mu^-$ channel which is suppressed by the dominant hadronic decay mode $U \rightarrow \pi^+ \pi^-$. To overcome this problem KLOE-2 plans to carry on also a new analysis by exploiting the $\pi^+ \pi^- \gamma$ channel. The detailed KLOE-2 physics program is presented in Ref. [27]. The KLOE reach at full statistics for the $\pi\pi\gamma$ channel is shown in Fig. 2 at $N_U/\sqrt{N_{\text{QED}}} = 2$ and a 2 MeV binning factor (green).

5. Conclusions

We searched for a light, dark vector boson through a study of the $\mu^+\mu^-\gamma$ ISR process by analysing a sample corresponding to a total integrated luminosity of 239 pb^{-1} . We found no evidence for such a U boson. We set an upper limit at 90% CL on the kinetic mixing parameter ε^2 between 1.6×10^{-5} and 8.6×10^{-7} in the 520–980 MeV mass range. A future analysis that exploits full KLOE statistics and an extended muon acceptance for the $\mu\mu\gamma$ channel as well as the investigation of $\pi\pi\gamma$ channel are planned.

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REFERENCES

- [1] B. Holdom, Phys. Lett. B 166 (1985) 196.
- [2] C. Boehm, P. Fayet, Nucl. Phys. B 683 (2004) 219.
- [3] P. Fayet, Phys. Rev. D 75 (2007) 115017.
- [4] Y. Mambrini, J. Cosmol. Astropart. Phys. 1009 (2010) 022.
- [5] M. Pospelov, A. Ritz, M.B. Voloshin, Phys. Lett. B 662 (2008) 53.
- [6] O. Adriani, et al., Nature 458 (2009) 607.
- [7] M. Aguilar, et al. Phys. Rev. Lett. 110 (2013) 141102.

- [8] P. Jean, et al., *Astronomy Astrophysics* 407 (2003) L55.
- [9] J. Chang, et al., *Nature* 456 (2008) 362.
- [10] F. Aharonian, et al., *Phys. Rev. Lett.* 101 (2008) 261104.
- [11] A. A. Abdo, et al., *Phys. Rev. Lett.* 102 (2009) 181101.
- [12] R. Bernabei, et al., *Eur. Phys. J. C* 56 (2008) 333.
- [13] M. Adinolfi, et al., *Nucl. Instrum. Meth. A* 488 (2002) 51.
- [14] M. Adinolfi, et al., *Nucl. Instrum. Meth. A* 482 (2002) 364.
- [15] D. Babusci et al., *Phys. Lett. B* 736 (2014) 459.
- [16] D. Babusci, et al., *Phys. Lett. B* 720 (2013) 336.
- [17] H. Czyż, A. Grzelinska, J.H. Kühn, G. Rodrigo, *Eur. Phys. J. C* 39 (2005) 411.
- [18] G. C. Feldman, R. D. Cousins, *Phys. Rev. D* 57 (1998) 3873; T. Junk, *Nucl. Instr. Meth. A* 434 (1999) 435; A. L. Read, *J. Phys. G: Nucl. Part. Phys.* 28 (2002) 2693.
- [19] H. Merkel, et al., *Phys. Rev. Lett.* 112 (2014) 221802.
- [20] S. Abrahamyan, et al., *Phys. Rev. Lett.* 107 (2011) 191804.
- [21] F. Archilli, et al., *Phys. Lett B* 706 (2012) 251.
- [22] D. Babusci, et al., *Phys. Lett. B* 720 (2013) 111.
- [23] P. Adlarson, et al., *Phys. Lett. B* 726 (2013) 187.
- [24] G. Agakishiev et al., *Phys. Lett. B* 731 (2014) 265.
- [25] J. P. Lees et al., *Phys. Rev. Lett.* 113 201801 (2014).
- [26] M. Pospelov, *Phys. Rev. D* 80 (2009) 095002.
- [27] G. Amelino-Camelia et al. (KLOE-2 Collaboration), *Eur. Phys. J. C* 68, 619 (2010).